International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 10, Issue 2, Apr 2020, 285–296


# STUDY AND OPTIMIZATION OF CUTTING PARAMETERS USING RSM FOR HIGH-SPEED PRECISION MACHINING OF TITANIUM ALLOYS

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***ABSTRACT***

***Titanium alloys Ti6Al4V largely used material in aerospace structural industries for its indispensable characteristics of the material for its good formability, strength, light weight and corrosion resistance. Most precision-machined components are made using titanium-based alloys in aerospace applications. The challenges in machining of titanium alloys remains the same and even tough during high cutting speed for precision milling of mating components . The titanium alloys are now grouped as difficult to machine due to its hardness and low thermal conductivity, where most of the heat generated in the cutting is passed to the cutting tool and results in tool wear. The optimum levels of high-speed precision finish machining of highly reactive material like titanium and its alloys is still unsolved. Optimization study of high-speed CNC machining parameters presented in this research paper are based on the experimental study on optimality conditions of the parameters like coolant flow rate, Spindle speed, tool feed rate and tool depth of cut on tool life for better surface smoothness in Titanium alloy precision CNC milling process.***

***KEYWORDS: High Speed Machining (HSM), Average Surface Roughness (Ra); Titanium Alloy, Response Surface Method (RSM) & Box Behnken Design (BB)***

**Received**: Dec 20, 2019; **Accepted**: Jan 10, 2020; **Published**: Mar 03, 2020; **Paper Id.**: IJMPERDAPR202025

**Original Article**

## 1. INTRODUCTION

High-speed machining (HSM) is utilized in a large portion of the assembling enterprises for machining harder materials with better precision for assembling aviation, car, guard and rocket parts than some other sort of industry. The HSM innovation contrasts from material to material, as the titanium amalgams are hard to machine, a powerful examination is required; and requirement for ideal arrangement of parameters is yet to be experimentally settled and demonstrated for a manufacturing plant implementation(5). This exploration work examines the conduct outside the Titanium material, as the machined surface of the material changes with the adjustment in cutting parameters like shaft speed, feed rate, profundity of cut and measure of coolant supply. The reaction of normal surface harshness (Ra) on machinability contemplates is evaluated and broke down for execution on select SMEs for optimality conditions (5). The thought is to examine the fast processing procedure of titanium combinations of various arrangements, by shifting diverse machining parameters and to break down the reaction utilizing the Response Surface Method (RSM) to get ideal arrangement of information parameters and furthermore the miniaturized basic scale changes that could cause the surface textural changes of machined workpieces. The RSM advancement put together is led with respect to a continuous contextual investigation on machining, particularly in CNC rapid machining of titanium compounds, which should have been performed to set up the characterizing parameters on

the said reaction (Ra), and the percent commitment of each factor through an ANOVA (Analysis of change) in view of DOE (Design of examinations), utilizing Box-Behnken Design (BB). It is seen that surface harshness is mostly impacted by the profundity of cut followed by cutting pace and feed rate and profundity of cut. Anyway, the inconstancy of each factor is non-direct and in various extents. The trial information accomplished is utilized for building up a relationship condition or target work for ideal normal surface unpleasantness (Ra).

## 2. LITERATURE REVIEW

A detailed literature survey on studies involving factors such as tool feed rate, spindle speed, depth of cut are considered to be controllable factors, whereas non-controlled factors such as non-homogeneity of the work piece, tool wear, machine-motion errors, formation of chips, vibrations and chatter are few examples, which cannot be controlled directly but can be minimized by providing an apt level of controllable factors (12). Chakradhar Bandapalli *et al*. [3] Investigations on high-speed end-milling of Ti alloy material using RSM dry conditions using the PVD-coated TiAlN tools presented the relationship of Ti6Al4V's surface roughness. A linear model is also fitted for thrust force prediction during dry cutting. 2FI (2-factor interaction) model is found to be fitted for cutting force prediction under dry cutting environment. The feed and depth of cut are the most sizeable factors affecting reducing pressure and account for 46.88% and 47.59% contribution inside the overall variability of model, respectively. Palanisamy, P. *et al*. [8] executed optimization of machining parameters using genetic algorithm and experimental validation for end-milling operations. In conclusion, it turned into surface roughness and became substantially influenced via feed rate followed by depth of cut. Rajendra Pawar *et al*. [10], Kasim, M. S. *et al*. [6], Atul Choudary *et al*. [2] proposed a theoretical technique towards the prediction of surface roughness [6,2]. In the above studies, coating, the surface integrity evaluation has been executed for dry high velocity machining of Ti-6Al-4V alloy and RSM to evaluate the life of cutting tool inserts for machining of Titanium alloys was studied. Quintana, G. *et al*. [9] proposed a theoretical approach towards the prediction of floor roughness. In the above research work, the restriction of analysis was done for single objective function, possible relation functions for multi-responses were not considered. Nambi Muthu Krishnan *et al*. [7] proposed the coolant influence in Ti alloy machinability. In this work, effect of flow of coolant rate influence with the surface roughness was studied. Alauddin, M. *et al*. [1] made a literature work on influence of machining parameters, like spindle speed, feed rate and axial depth of cut by developing models for the prediction of surface roughness and tool life. Zain, A. M. *et al*. [11] made a literature survey on the various researches on the prediction of an optimized set of cutting parameters in terms of surface roughness using genetic algorithm in end milling process and was found to be very limited. Coker, S. A. et al. [4] performed the optimization of surface roughness by using experimental investigations. In this work, based on the optimization predicted values, the spindle speed and depth of cut with proper feed rate gives the better response for surface finish and material removal rate. Gologlu, C. *et al*. [5] made a literature survey on the design of experiments for the machining parameters optimization and identified the optimized values of surface roughness. In the above carried out researches, one can find the application of higher optimization tools, but the work considered was constrained to one objective function (5). All the machining processes are focused on providing higher quality in reduced time of machining. Therefore, it becomes mandatory to study the effect of accompanied responses to arrive at the best possible machining parameters. From the literature sources (12), it reveals that only few researches have been carried out in determining the optimized set of machining parameters in end milling process of titanium alloy. In this study, an investigation is carried out on the effect of process parameters, such as spindle speed, feed rate and depth of cut-on response factor as average surface roughness (Ra) in end milling using RSM approach (12). The experiments were carried out using 3-axis vertical CNC machine and 12-mm

diameter High-Speed Steel (HSS) end mill cutters. Based on the confirmatory runs, the mathematical model was developed and it meets the desired level of expectation.

## 3. OPTIMIZATION METHOD AND PROPOSED RSM APPROACH

Response Surface Methodology (RSM) explores the relationships between many instructive variables and one or a lot of response variables. The plan of RSM is to use a sequence of designed experiments to get a best response. By employing a second-degree polynomial model, it is straightforward to estimate and apply even once very little is understood regarding the method. Applied mathematical approaches like RSM may be used to maximize the assembly of a special substance by optimization of operational factors. In distinction to traditional ways, the interaction among method variables may be determined by applied math techniques. The experiment method mentioned in second level Factorial Experiments and extremely third Factorial styles facilitate the experimenter establish factors that have an effect on the response. Once the necessary factors are known, subsequent step is to work out the settings for these factors that end in the optimum worth of the response. The optimum worth of the response could either be most worth or a minimum worth, relying upon the method. Regression models are used for the analysis of the response, because the focus is now on the character of the link between the response and therefore the factors instead of identification of the necessary factors.

### 3.1 Surface Roughness

Batch and job order kind industries contemplate surface roughness as the most significant quality indicator of performance and are evaluated in numerous forms, like average roughness (Ra), root–mean–square (RMS) and most peak-to-valley roughness (Rmax). Response surface methodology (RSM) may be a tool that has been extensively employed for the modeling and analysis of issues involving variables influencing a response of interest.

$$\mathbf{Ra = \varepsilon A^{k1} B^{k2} C^{k3} D^{k4},} \tag{1}$$

where Ra : predicted surface roughness (microns)

ε: response error

A: spindle speed (rpm)

B: depth of cut (mm)

C: feed rate (mm/rev)

D: Coolant flow rate (l/min)

$k_1$, $k_2$, $k_3$, $k_4$: modal parameters estimated from experimental data

By performing regression analysis on the experimental data, one can obtain a relevant model that provides the relationship between the variables and the responses considered. The theoretical equation thus arrived by various researches on this behalf is given by the equation 1.

The above equation can also be written in the following form:

$$\ln Ra = \ln \varepsilon + k_1 \ln A + k_2 \ln B + k_3 \ln C + k_4 \ln D \tag{2}$$

The linear model of the above equation on a logarithmic scale of 1 is given by

$$y = \alpha_0 x_0 + \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4 D, \tag{3}$$

where y is the response on a log scale of 1; A, B, C, D are the logarithmic transformations of spindle speed, depth of cut, feed rate and coolant flow rate, respectively. The second-order model of the above is given by

$$y' = y - \varepsilon = \alpha_0 x_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{33} x_3^2 + \alpha_{44} x_4^2 + \alpha_{12} x_1 x_2 + \alpha_{13} x_1 x_3 + \alpha_{14} x_1 x_4 + \alpha_{23} x_2 x_3 + \alpha_{24} x_2 x_4 + \alpha_{34} x_3 x_4, \tag{4}$$

where y’ : Estimated response

Y: Roughness on logarithmic scale

$\varepsilon$: Experimental error

$\alpha_0$: Free term of the regression equation

$\alpha_1$, $\alpha_2$: Coefficients, linear terms

$\alpha_{11}$, $\alpha_{22}$: Coefficients, quadratic terms

$\alpha_{12}$, $\alpha_{13}$: Coefficients, interaction terms

### 3.2 Design of Experiment

The entire study is dispensed within the following sequence:

- The experiments are conducted on a 3-axis CNC vertical machining center with tool steel finish mill cutter of 12 mm diameter having four flutes with 22 mm overhung length beneath wet condition.
- The method parameters thought-about ar spindle speed (rpm), feed rate (mm/min), depth of cut (mm), fluid rate of flow (bar).
- The surface roughness is measured by employing a surface roughness tester.
- The experiment is conducted at three levels, four issues with Box Behnken style having 20 sequences of experimental runs.
- Second-order quadratic model developed for the prediction of surface roughness is checked for its adequacy mistreatment analysis of variance.
- Design Expert software version 11 is employed to see the optimized set of machining parameters that ends up in predicting the worth of average surface roughness (Ra).
- Validation of the results confirmed by experimental runs.

Large number of parameters affects the surface roughness, namely spindle speed, feed rate, depth of cut and coolant flow, etc. Nowadays, the controllable factors considered are spindle speed (rpm), depth of cut (mm), feed rate (mm/min) and coolant flow (bar). Based on the manufacturer’s specifications, the ranges are fixed and researches carried out. HSS end mill cutter of 12 mm diameter with four flutes is selected. The overhung length of the tool is maintained at 22 mm to avoid chatter that could possibly affect the responses. The upper limit of a given factor was coded as (+1) and the lower limit was coded as (−1). The coded values for intermediate values were calculated using Eq. (1).

$$X_i = 2\{2X - (X_{max} + X_{min})\}\ X_{max} - X_{min}, \quad (5)$$

where $X_i$ = required coded value of variable X

The value of $X$ varies from $X_{min}$ to $X_{max}$

Table 1. Displays the details of the process parameters considered and their limits

**Table 1: Parameters and Levels**

| Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Spindle Speed (rpm) | 4000 | 5000 | 6000 |
| Depth of Cut (mm) | 0.5 | 1 | 1.5 |
| Feed Rate (mm/min) | 600 | 900 | 1200 |
| Coolant flow rate (bar) | 0.75 | 1.37 | 2 |

The work piece taken for experimentation is of size 75 mm × 30 mm × 12 mm rectangular block prepared from titanium alloy. The chemical composition of the base material is presented in Table 3. The experiment was conducted on 3-axis CNC Vertical Machining Center with high-speed steel end mill cutter of 12 mm diameter under flooded condition. The surface roughness is measured by using a surface roughness tester (Mahr RML-292), as displayed in figure. 1.

**Table 3: Chemical Composition**

| Material | Percentage |
|---|---|
| Carbon | 0.10% |
| Vanadium | 4.00% |
| Titanium | 89% |
| Ferrous | <=0.020% |
| Nitrogen | <=0.030% |
| Oxygen | <=0.020% |
| Hydrogen | <=0.015% |
| Aluminium | 6.00% |

### 3.3 Box-Behnken Design

BBD is used to perform the experimental runs. Initially, four factors with three levels are assigned as input variables with levels represented by +1 for upper limits and -1 for lower limits. One response is assigned, namely surface roughness. The experimental sequences generated in response are reflected in table 2.

**Table 2: Box-Behnken Experimental Sequences with Responses**

| Spindle Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) | Coolant Flow Rate (Bar) | Surface Roughness (Microns) |
|---|---|---|---|---|
| 4000 | 900 | 1.0 | 0.75 | 1.431 |
| 5000 | 1200 | 1.0 | 2.00 | 1.293 |
| 4000 | 900 | 1.5 | 1.37 | 1.222 |
| 6000 | 900 | 1.0 | 0.75 | 0.842 |
| 5000 | 1200 | 1.0 | 0.75 | 1.539 |
| 5000 | 900 | 0.5 | 0.75 | 0.854 |
| 5000 | 600 | 1.0 | 0.75 | 0.971 |
| 5000 | 900 | 1.0 | 1.37 | 1.154 |
| 5000 | 900 | 1.5 | 2.00 | 0.471 |
| 4000 | 600 | 1.0 | 1.37 | 1.775 |
| 5000 | 900 | 1.5 | 0.75 | 2.545 |
| 6000 | 600 | 1.0 | 1.37 | 2.564 |
| 5000 | 900 | 0.5 | 2.00 | 0.754 |
| 6000 | 900 | 1.5 | 1.37 | 2.140 |

| | | | | |
|---|---|---|---|---|
| 6000 | 1200 | 1.0 | 1.37 | 1.957 |
| 5000 | 900 | 1.0 | 1.37 | 4.094 |
| 5000 | 1200 | 0.5 | 1.37 | 2.581 |
| 5000 | 900 | 1.0 | 1.37 | 1.294 |
| 6000 | 900 | 1.0 | 2.00 | 0.863 |
| 5000 | 600 | 0.5 | 1.37 | 0.877 |
| 4000 | 900 | 0.5 | 1.37 | 1.357 |
| 5000 | 900 | 1.0 | 1.37 | 1.005 |
| 5000 | 1200 | 1.5 | 1.37 | 2.378 |
| 4000 | 900 | 1.0 | 2.00 | 6.107 |
| 5000 | 600 | 1.0 | 2.00 | 5.453 |
| 6000 | 900 | 0.5 | 1.37 | 5.325 |
| 5000 | 600 | 1.5 | 1.37 | 5.653 |
| 5000 | 900 | 1.0 | 1.37 | 2.439 |
| 4000 | 1200 | 1.0 | 1.37 | 2.669 |

### 3.4. Response Surface Model for the Prediction of Surface Roughness

Design Expert software version 11 is used to perform rigorous analysis on the experimental data and a second-order quadratic model is developed for the prediction of surface roughness. Analysis of variance (ANOVA) is performed to check the adequacy of the model created, as displayed in table 4.

**Table 4: ANOVA for Surface Roughness**

| ANOVA for Response Surface Quadratic Model | | | | | |
|---|---|---|---|---|---|
| Analysis of Variance Table | | | | | |
| **Source** | **Sum of Squares** | **df** | **Mean Square** | **F Value** | **Prob > F** |
| Model | 30.80 | 14 | 2.20 | 0.7350 | 0.7139 significant |
| A-Spindle Speed | 0.0631 | 1 | 0.0631 | 0.0211 | 0.8867 |
| B-Feed Rate | 1.98 | 1 | 1.98 | 0.6618 | 0.4295 |
| C-Depth of cut | 0.5901 | 1 | 0.5901 | 0.1971 | 0.6639 |
| D-Coolant flow rate | 3.81 | 1 | 3.81 | 1.27 | 0.2784 |
| AB | 0.5633 | 1 | 0.5633 | 0.1881 | 0.6711 |
| AC | 2.33 | 1 | 2.33 | 0.7768 | 0.3930 |
| AD | 5.42 | 1 | 5.42 | 1.81 | 0.1999 |
| BC | 6.20 | 1 | 6.20 | 2.07 | 0.1722 |
| BD | 5.59 | 1 | 5.59 | 1.87 | 0.1934 |
| CD | 0.9742 | 1 | 0.9742 | 0.3254 | 0.5774 |
| A^2 | 0.5787 | 1 | 0.5787 | 0.1933 | 0.6669 |
| B^2 | 1.50 | 1 | 1.50 | 0.5012 | 0.4906 |
| C^2 | 0.0088 | 1 | 0.0088 | 0.0029 | 0.9575 |
| D^2 | 0.7606 | 1 | 0.7606 | 0.2541 | 0.6221 |
| Residual | 41.91 | 14 | 2.99 | | |
| Cor Total | 72.72 | 28 | | | |
| Std. Dev. | 1.73 | | R-Squared | 0.4236 | |
| Mean | 2.19 | | Adj R-Squared | 0.1528 | |
| C.V. % | 78.89 | | Pred R-Squared | -1.0314 | |
| PRESS | N/A | | Adeq Precision | 3.2859 | |

From table 4, it is evident that “model F value” of 0.7350 with a “model P value” is less than 0.0500 implies that the selected model is significant. If the values are greater than 0.1000 then the model terms is said to be not significant. The P value <0.0500 represents that there is only a 0.02% chance that such a model could occur due to noise. Surface plots are plotted to provide a clear view of the relationship between the response and the process parameters. The measures of $R^2$, Adj $R^2$, and Pred $R^2$ indicate the goodness of fit for the models and are close to 1.

***Objective Function for Surface Roughness* (*Ra*)**

**Minimize (Ra) = 2.012+ 0.479A - 0.395B +0.4767C + 0.7130D -0.561AB -0.752A.C - 1.26 AD – 1.41BC – 1.39BD – 0.5135CD** (6)

## 4. RESULTS AND DISCUSSIONS ON SURFACE ROUGHNESS

The surface interaction in Figure 2 displays plot of spindle speed and profundity of cut over surface roughness. Least roughness is accomplished when the profundity of cut is kept up as far as possible and axle speed is differed between 4000 rpm and 6000 rpm. Additionally, the better surface roughness is conceivable when the profundity of cut is kept up between 0.5 mm and 1.5 mm. Along these lines, to accomplish the ideal yield for the work piece considered, it tends to be presumed that shaft speed and profundity of slice are to be at lower level. Figure 3 displays the surface collaboration plot of shaft speed and feed rate over surface harshness. From the diagram, one can recognize that better surface completion can be achieved by changing the axle speed and profundity of cut. From this, it states that the axle speed is conversely relative to profundity of cut. This reveals a crucial job in deciding the advanced arrangement of machining parameters, as one have to recognize the setting between feed rate and axle speed

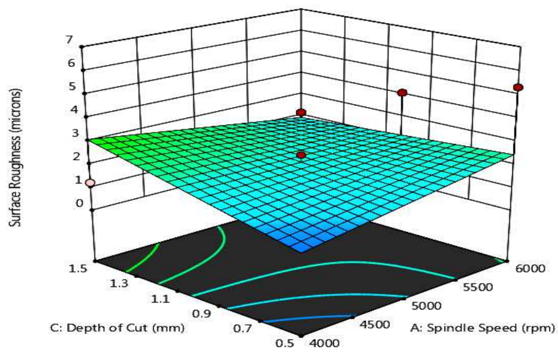


**Figure 2: Surface Interaction Plot of Spindle Speed and Depth of Cut over Surface Roughness.**

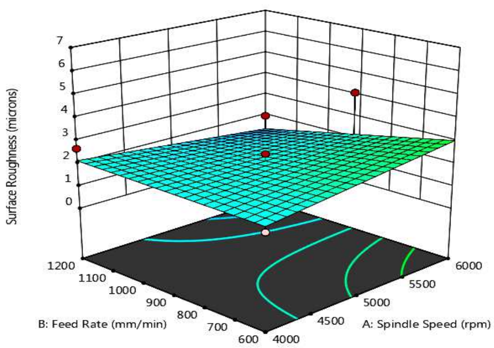


**Figure 3: Surface Interaction Plot of Spindle Speed and Feed Rate over Surface Roughness.**

Figure 4 displays the surface communication plot of axle speed and coolant stream rate. From the diagram, it is obvious that coolant follows a consistent example with axle speed. With contrasted and different parameters, the coolant stream rate impact is seen as least. Simultaneously, from the chart, it is indicated that better outcomes can be achieved at the lower furthest reaches of coolant stream rate and medium degree of shaft speed.

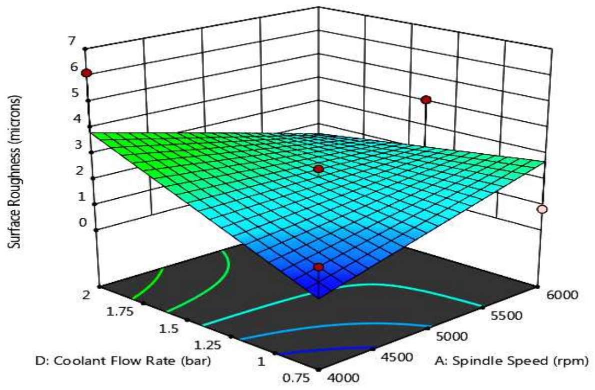


**Figure 4: Surface Interaction Plot of Spindle Speed and Coolant Flow Rate over Surface Roughness.**

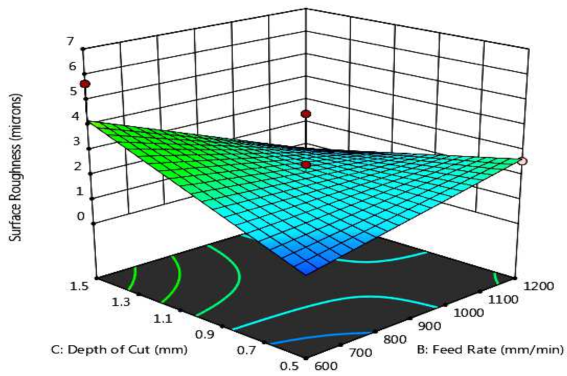


**Figure 5: Surface Interaction Plot of Feed Rate and Depth of Cut over Surface Roughness.**

Figure 5 displays the surface collaboration plot of feed rate and profundity of cut. From the diagram, it is obvious that the ideal harshness can be accomplished by keeping up the feed rate between 600 and 1200 mm/min and profundity of slice between 0.5 mm and 1.5 mm. One can reason that for accomplishing the ideal reaction, higher feed rate and lower profundity of slice is to be kept up. Figure 6 reveals the surface interaction plot of depth of cut and coolant flow rate. From the graph, one can identify that flow of coolant follows a steady pattern with depth of cut. Here, the coolant flow rate is found to be least when compared with other parameters.

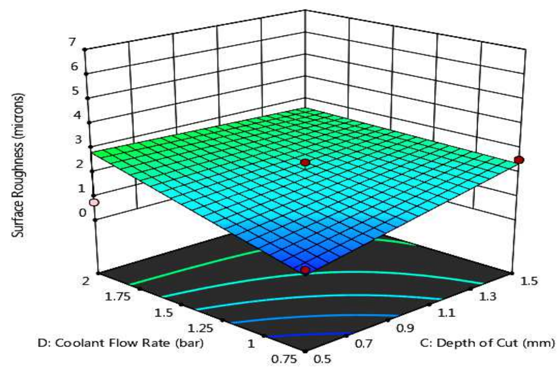


**Figure 6: Surface Interaction Plot of Depth of Cut and Coolant Flow Rate over Surface Roughness.**

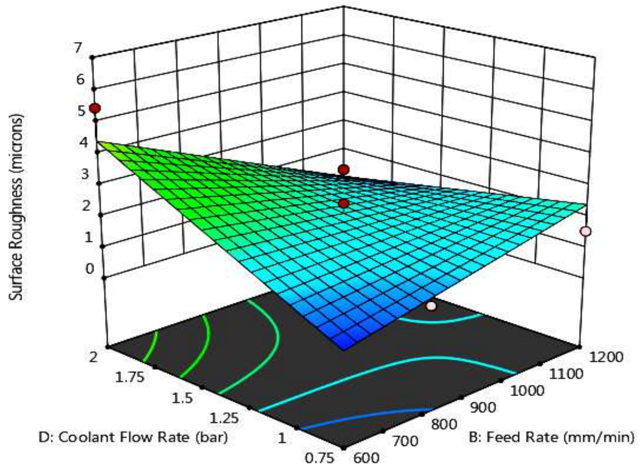


**Figure 7: Surface Interaction Plot of Coolant Flow Rate and Feed Rate over Surface Roughness.**

The relationship interpreted by the graph reveals that better results can be attained at the lower limits of coolant flow rate and depth of cut. Figure 7 reveals the surface interaction plot of feed rate and coolant flow rate. From the graph, one can identify that flow of coolant follows a steady pattern with feed rate. When compared with other parameters, the effect of coolant flow rate is found to be almost the same with minimum deviations. The optimized set of parameters is thus attained by the above analysis and is displayed in table 5. Objectives: Roughness – minimize Table 5 reveals the effect of the parameters on the response. The combined measure of the roughness is found to be 1.621, whereas when roughness alone is considered it is found to be 1. This clearly proves that the effect of Spindle Speed and Depth of cut with desirable feed rate provides better finish on the work piece considered.

**Table 5: Optimized Set by Box-Behnken Design**

| Spindle Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) | Coolant Flow Rate (Bar) | Roughness (Ra) Microns | Desirability |
|---|---|---|---|---|---|
| 4793.96 | 921.719 | 1.362 | 0.807 | 1.621 | 0.87 |

## 5. VALIDATION OF THE MODEL

The surface roughness as per Box-Behnken design is found in table 2. From this, the regression equation developed is displayed in equation 6 for response roughness, respectively. Table 6 reveals the response comparison between predicted and measured values. From table 6, it is evident that the RSM-predicted optimum conditions are found to be within ±1.5% variations, which proves the fit of the model. Therefore, it is concluded that the experimental results of response, as predicted by RSM, is efficient to be considered for machining. Figure 8 reveals the variation of predicted and measured values in graphical form with the observations that it is considerably close and small variations within acceptable levels of variations, then the method adopted to solve is most suited for the optimization challenges of titanium alloys and metal matrix composites.

**Table 6: Predicted Measured Values of the Responses**

| Spindle Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) | Coolant Flow Rate (Bar) | Ra- RMS Prediction Value (Microns) | Ra- Measured Value (Microns) |
|---|---|---|---|---|---|
| 4793 | 921 | 1.36 | 0.80 | 1.621 | 1.68 |
| 4793 | 921 | 1.36 | 0.80 | 1.621 | 1.82 |
| 4793 | 921 | 1.36 | 0.80 | 1.623 | 1.52 |
| 4793 | 921 | 1.36 | 0.80 | 1.624 | 1.72 |
| 4793 | 921 | 1.36 | 0.80 | 1.623 | 1.92 |

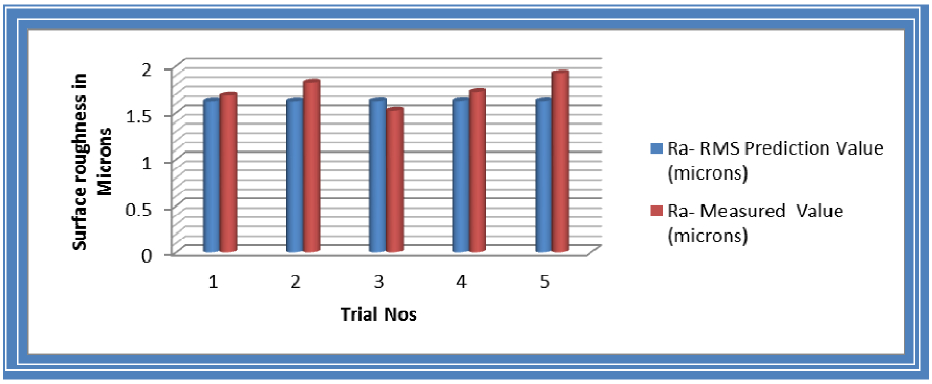


**Figure 8: Comparison of Predicted Vs Actual Responses.**

## 6. CONCLUSIONS

The analyses at different levels are led by utilizing Box Behnken structure and second request scientific model is created for anticipating the reaction of normal surface harshness by machining with end processing activity for titanium compound (particularly, β Ti amalgams). HSS end factory shaper of width 12 mm, 4 woodwinds having 22 mm overhung length is utilized for machining. The arrangement of trials is done by fluctuating the procedure parameters, for example, axle speed, feed rate and profundity of cut and coolant stream rate. The numerical model is made by two-phase approach and the model made is broken down with ANOVA and advanced with RSM strategy for the arrangement of machining parameters. The numerical model created by second request gives precise outcomes to the anticipated estimations of reaction near genuine qualities found in the investigations. The resultant condition is seen with high certainty level of 93%. In view of the test results, it is discovered that the parameters – axle speed and feed rate reveals better effect on surface unpleasantness. The best least anticipated surface unpleasantness esteem prescribed by RSM strategy is 1.621 microns for the titanium amalgam utilized in the examination for exploring the achieved outcome. In light of the model approval, it is affirmed that the anticipated qualities was discovered superior to the connection with observed values.

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